



Dendroclimatological potential of conifers in Pakistan Karakoram-Himalaya region

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Abstract: Long tree growth chronologies, also known as "time lines of the environment", have gained rapid improvement in climatically sensitive Pakistan Karakoram-Himalaya over the past three-five decades. But a quantitative assessment of research effort in this area is missing. Here, for the first time, we conducted a quantitative synthesis using descriptive, inferential, multivariate and ecological statistical methods to integrate 78 published dendrochronological studies conducted in Pakistan between 1989–2022 that include eleven conifer species and 22 longest-reported ring-width chronologies. We estimated the distribution of research effort (Wilson 95% confidence intervals), non-parametric group differences (Kruskal-Wallis), information-theoretic diversity (Shannon-Wiener, Simpson, Pielou), contingency independence between species and research domains (chi-square and Cramér's V), correlation and ordinary least-squares regression of elevation on chronology length, estimated elevational niche overlap (Pianka's index) and site-sharing (Jaccard similarity) and synthesized the data through principal component analysis (PCA) and Ward's hierarchical clustering. *Pinus wallichiana* (20.5%, 95% CI 13.0–30.8%), *Abies pindrow* (16.7%, 10.0–26.5%), *Picea smithiana* (15.4%, 9.0–25.0%) and *Cedrus deodara* (14.1%, 8.1–23.5%) emerged as the most-studied taxa, while *Taxus baccata* and three *Juniperus* species were markedly underrepresented. Chronologies ranged in length from 51 to 1224 years, with a mean of 445 years (SD = 366) and the mean *Picea smithiana* chronology length rivaled the longest chronology lengths of *Juniperus excelsa* and *Juniperus turkestanica*. The distribution of species was even (Pielou's $J' = 0.90$) and a positive monotonic correlation existed between the longest chronology and site elevation (Spearman $\rho = 0.70$, $p = 0.035$). The number of papers published per year showed high linear association ($r^2 = 0.86$, $p < 0.001$), with the PCA of the underlying profiles of the trees explaining 87.5% variance on two principal axes and three clusters with an ecological basis. These findings provide the first quantitative, empirical guidance on priorities in improving the Pakistan dendrochronology record and suggest the need for a more targeted effort to obtain juvenile wood samples of the under-represented *Junipers*, yews and hardwoods to address significant temporal and elevational gaps in the Asian tree-ring record.

Keywords: the Third Pole, dendrochronology, ring-width chronology, systematic review.

Introduction

Tree rings remain one of the most commonly used, high information sources of environmental archives. The annually resolved, absolutely dated records of tree-ring width and stable isotopes allow for the reconstruction of climate, hydrology and ecosystem activity on multi-century to multi-millennial timescales (Fritts 1971; Hughes *et al.* 2010). Pakistan, at the tectonic and climatic nexus of the Karakoram, Himalaya and Hindu Kush, is home to one of the

world's longest-lived stands of conifers and a globally important source of high-elevation tree-ring data (Treydte *et al.* 2006; Ahmed *et al.* 2009a, 2011, 2012; Asad *et al.* 2017a). Although the quantity of research in the field of dendrochronology has been steadily increasing since the late 1980s (Ahmed 1989), the field has never been mapped using robust quantitative statistical techniques.

The Hindu Kush-Karakoram-Himalaya (HKKH) region is experiencing high rates of climate change (Asad



and Zhu 2018; Dimri *et al.* 2021; Muhammad *et al.* 2021; Khan *et al.* 2022) much greater than the global average, as well as dissimilar temperature and precipitation responses in comparison to the Northern Hemisphere (Zafar *et al.* 2016; Asad *et al.* 2017b; Luqman *et al.* 2021; Zhu *et al.* 2021). So, it is essential to understand where the best-characterized species, elevations, valleys and research areas for chronology development, climate-topic relationships, climate reconstruction, isotopes, *etc.* are and where there are gaps is critical for planning future research activities, forest management and climate adaptation.

While qualitative reviews of Pakistani dendrochronology have not existed, no such works have applied statistical approaches to (i) assess if research effort is equally spread across species, (ii) quantify the variance of observed research-effort proportion, (iii) test if there is elevation-dependent variation in chronology length, (iv) cluster species on the basis of species-specific, multivariate research profiles, or (v) measure trends in research productivity over time. This type of quantitative analysis is now provided as a routine contribution to many research reviews in ecology and biogeography (Gaire *et al.* 2020;

Gautam *et al.* 2020) and offers a more rigorous, replicable and representative basis for informing science and policy.

The present review seeks to (i) establish a statistical synopsis of all published dendrochronological studies conducted in Pakistan up to December 2022; (ii) use inferential statistics, multivariate ordination and hierarchical clustering to describe the distribution of research-effort, the variability in chronology lengths, the spread across research-domains and the structure of elevational niches; and (iii) delineate explicit data-gaps and recommend data-driven priorities for future dendrochronological research in Pakistan.

Methods

We searched the literature in Google Scholar, Web of Science and ResearchGate to identify all the dendrochronology research published in Pakistan between 1989, the earliest study of Ahmed (1989) and December 2022 (Fig. 1). The search terms were one or more of Pakistan, dendrochronology, tree-ring, chronology length, climate reconstruction and HKKH (Tables 1 and 2).

Table 1. Length of the longest ring width chronologies of selected tree species from Pakistan.

Plant species	Chronology length in years	Duration (AD)	Study Area	Reference
<i>Cedrus deodara</i>	51	1964–2015	Koozah gali	Khan <i>et al.</i> (2018a)
<i>Abies pindrow</i>	61	1954–2015	Ayubia	Khan <i>et al.</i> (2018a)
<i>Pinus roxburghii</i>	75	1940–2015	Ghora gali	Khan <i>et al.</i> (2018a)
<i>Pinus wallichiana</i>	106	1904–2015	Main Murree	Khan <i>et al.</i> (2018a)
<i>Taxus baccata</i>	131	1888–2019	Kalam Forest Division	Muhammad <i>et al.</i> (2021)
<i>Abies pindrow</i>	237	1750–1987	Murree and Ayubia	Ahmed (1989)
<i>Pinus gerardiana</i>	271	1737–2008	Chaprot	Zafar <i>et al.</i> (2016)
<i>Pinus wallichiana</i>	280	1730–2010	Ganji Skardu	Ali and Ali (2014)
<i>Abies pindrow</i>	320	1680–2000	Ayubia	Ahmed <i>et al.</i> (2010a)
<i>Pinus wallichiana</i>	350	1500–1850	Chaprot and Haramosh	Luqman <i>et al.</i> (2021)
<i>Pinus wallichiana</i>	379	1635–2014	Haramosh valley	Asad and Zhu (2018)
<i>Abies pindrow</i>	394	1620–2014	Sharakot valley	Khan <i>et al.</i> (2018b)
<i>Pinus wallichiana</i>	437	1575–2012	Bagrot valley	Asad <i>et al.</i> (2017a)
<i>Pinus smithiana</i>	485	1523–2008	Jutial	Zafar <i>et al.</i> (2016)
<i>Abies pindrow</i>	500	1500–2000	Astore	Ahmed <i>et al.</i> (2010a)
<i>Pinus gerardiana</i>	600	1400–2000	Kalash	Ahmed <i>et al.</i> (2010b)
<i>Pinus wallichiana</i>	606	1409–2015	Chiraah valley	Asad <i>et al.</i> (2018)
<i>Pinus smithiana</i>	606	1400–2006	Chera and Nalter	Ahmed <i>et al.</i> (2009a)
<i>Pinus wallichiana</i>	700	1300–2000	Astore	Ahmed <i>et al.</i> (2010b)
<i>Juniperus excelsa</i>	747	1260–2007	Bagrot and Morkhun	Ahmed <i>et al.</i> (2011)
<i>Juniperus excelsa</i>	1224	950–1998	Morkhun and Bagrot	Treydte <i>et al.</i> (2006)
<i>Juniperus turkestanica</i>	1224	950–1998	Morkhun and Bagrot	Treydte <i>et al.</i> (2006)

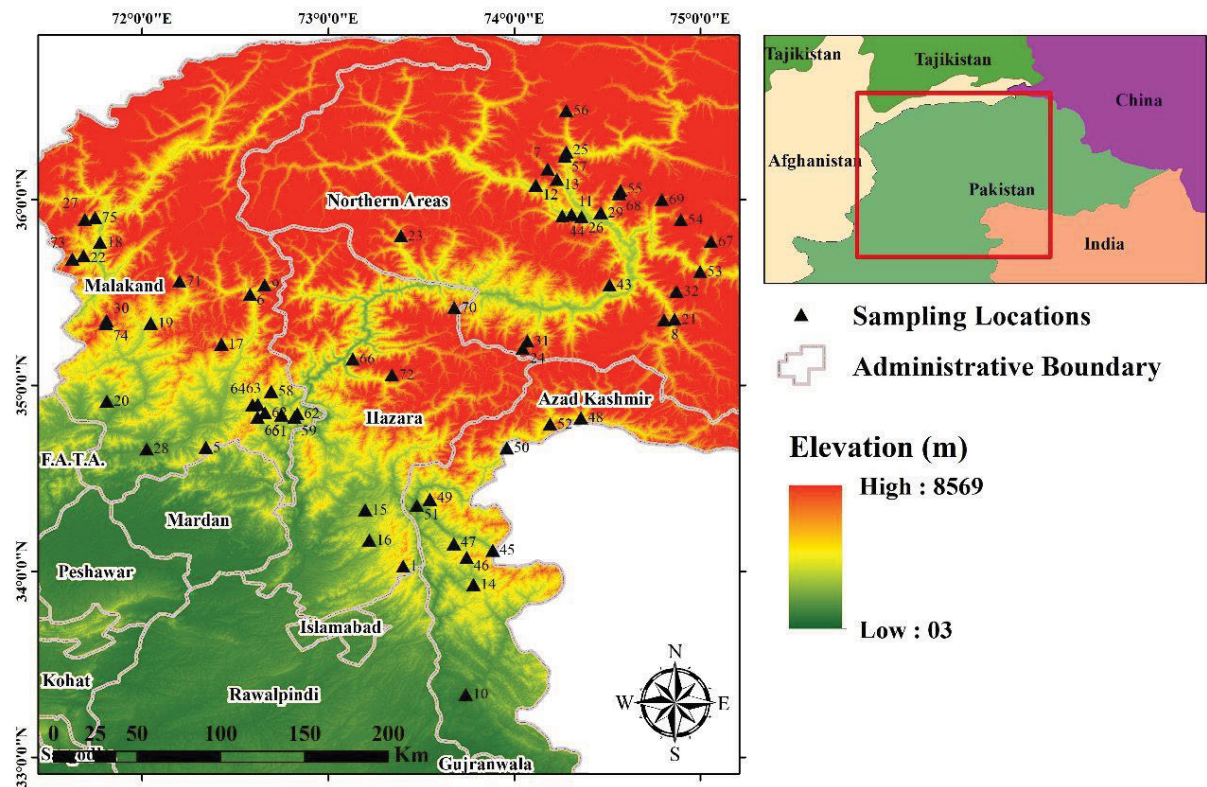


Fig. 1. Physiographical map of northern Pakistan with the major mountainous regions and the sites of dendrochronological studies reported in Table 2. The black triangles (▲) show the dendrochronological study sites of 1–78, referring to study serial number (No.) in Table 2.

We only included original peer-reviewed research articles that produced tree-ring chronologies or climate-growth relationships for species growing in Pakistan. We excluded reviews, book chapters and theses to prevent double counting. We removed duplicates from different databases. The data for each selected study were coded along seven variables: (1) lead author and year, (2) species,

(3) study location, (4) minimum and maximum elevations (m a.s.l.), (5) research theme(s) covered, (6) length of the chronology, when reported in years, (7) time period (AD) spanned (Tables 1 and 2).

In all, we found 78 studies with eleven conifer species; see Table 1 for longest chronologies and Table 2 for the full list of dendrochronological studies and their locations.

Table 2. List of dendrochronological related research in Pakistan. Abbreviations: CB – chronology building, CGR – climate growth relationship, CR – climate reconstruction, DA – dendroseismological analysis, DP – dendroseismological potential, GR – growth rate, PR – precipitation reconstruction, TR – temperature reconstruction, TROI – tree-ring oxygen isotopes.

No.	Authors	Study area	Elevation (m)	Research domain
<i>Abies pindrow</i>				
01	Ahmed (1989)	Murree and Ayubia	2000–3000	CB
02	Ahmed and Sarangezai (1991)	Murree and Ayubia	2195–3048	CB
03	Ahmed <i>et al.</i> (2009b)	Lalazar (Murree)	1400–2700	CGR
04	Ahmed <i>et al.</i> (2010a)	Astore and Ayubia	3450–2500	CGR
05	Ahmed <i>et al.</i> (2011)	Bumburet (Kalash)	2550–3450	CB
06	Bokhari <i>et al.</i> (2013)	Sudhan Gali and Pir Chinasi	833–2900	CGR and DA
07	Iqbal <i>et al.</i> (2017)	Shangla	1990–2810	CGR
08	Khan <i>et al.</i> (2018a)	Ayubia	2291	CB and CGR
09	Khan <i>et al.</i> (2018b)	Sharakot valley	2727	CB and CGR
10	Iqbal <i>et al.</i> (2020)	Shangla	1990–2810	GR
11	Khan <i>et al.</i> (2021)	Harban valley	3100–3250	CB and TR

Table 2 - continued.

No.	Authors	Study area	Elevation (m)	Research domain
12	Muhammad <i>et al.</i> (2021)	Kalam Forest Division	1900–4600	CB and CGR
13	Khan <i>et al.</i> (2022)	Ayubia	2672	CB and PR
<i>Cedrus deodara</i>				
14	Ahmed and Sarangezai (1991)	Kalam	2134	CB and CGR
15	Ahmed <i>et al.</i> (2009b)	Ziarat (Drosh) Chitral	1400–2700	GR and CGR
16	Ahmed <i>et al.</i> (2010)	Tangir (Diamer)	2320	CB and CGR
17	Ahmed <i>et al.</i> (2011)	Chitral-Gol National Park	2550–3450	CB and CGR
18	Ahmed <i>et al.</i> (2012)	Tangir (Diamer)	2320	CB and CGR
19	Bokhari <i>et al.</i> (2013)	Kail and Keran	833–2900	CGR and DP
20	Iqbal <i>et al.</i> (2017)	Shangla	1990–2810	GR and CGR
21	Khan <i>et al.</i> (2018a)	Koozah gali	2291	CB and CGR
22	Iqbal <i>et al.</i> (2020)	Shangla	1990–2810	GR and CGR
23	Sajad <i>et al.</i> (2021)	Kumrat valley	1420	CGR
24	Muhammad <i>et al.</i> (2021)	Kalam Forest Division	1900–4600	CB and CGR
<i>Juniperus excels</i>				
25	Ahmed and Sarangezai (1991)	Susnamana forest, Beba khur-wari, Ziarat and Pashin.	2438	CB and CGR
26	Esper (2000)	Hunza valley	3600–3900	CR
27	Treydte <i>et al.</i> (2006)	Morkhun and Bagrot	2900–3900	CB, PR and TROI
28	Ahmed <i>et al.</i> (2010b)	Babusar (Diamer)	3200	CB and CGR
29	Sarangzai and Ahmed (2011)	Ziarat Mountains	2000–3000	GR and CR
30	Ahmed <i>et al.</i> (2012)	Babusar (Diamer)	3200	CB and CGR
<i>Juniperus semiglobosa</i>				
31	Esper <i>et al.</i> (2002)	Northwest Karakoram region	2800–3900	CR
32	Esper <i>et al.</i> (2007)	Karakoram range mountains	2700–3900	CB
<i>Juniperus seravchanica</i>				
33	Esper <i>et al.</i> (2002)	Northwest Karakoram	2800–3900	CR
34	Esper <i>et al.</i> (2007)	Karakoram mountains	2700–3900	CB
<i>Juniperus turkestanica</i>				
35	Esper (2000)	Hunza valley	3600–3800 and 3900	CR
36	Esper <i>et al.</i> (2002)	Northwest Karakoram	2800–3900	CR
37	Treydte <i>et al.</i> (2006)	Morkhun and Bagrot	2900–3900	CB, PR and TROI
38	Esper <i>et al.</i> (2007)	Karakoram mountains	2700–3900	CB
<i>Pinus gerardiana</i>				
39	Ahmed and Sarangezai (1991)	Shinghar forest	274.32	CB and CGR
40	Ahmed <i>et al.</i> (2010b)	Kalash	2530	CB and CGR
41	Ahmed <i>et al.</i> (2010c)	Chaprot	2850	CB and GR
42	Ahmed <i>et al.</i> (2011)	Bumburet (Kalash), Chitral Gol-National Park, Joti (Chilas)	2550–3450	CB and GR
43	Ahmed <i>et al.</i> (2012)	Chaprot	2850	CB and CGR
44	Zafar <i>et al.</i> (2016)	Chaprot	2850–3300	CB and TR

Table 2 - continued.

No.	Authors	Study area	Elevation (m)	Research domain
<i>Picea smithiana</i>				
45	Ahmed and Naqvi (2005)	Nalter, Astor, Kalam and Mian-dum (Swat)	2300–3500	CB and CGR
46	Ahmed <i>et al.</i> (2009a)	Chera and Naltar (Gilgit)	3100–3400	CB and CGR
47	Ahmed <i>et al.</i> (2009b)	Nalter Valley	1400–2700	GR and CGR
48	Ahmed <i>et al.</i> (2010c)	Jutial (Gilgit)	3250	CB and DP
49	Ahmed <i>et al.</i> (2011)	Chera and Naltar (Gilgit)	2550–3450	CB and GR
50	Ahmed <i>et al.</i> (2012)	Jutial (Gilgit)	3250	CB and CGR
51	Bokhari <i>et al.</i> (2013)	Azad Kashmir	833–2900	CGR and DP
52	Zafar <i>et al.</i> (2016)	Kargah	2850–3300	CB and TR
53	Iqbal <i>et al.</i> (2017)	Shangla	1990–2810	GR and CGR
54	Hussain <i>et al.</i> (2018)	Istak Skardu	2600–3600	GR
55	Khan <i>et al.</i> (2020)	Jutail and Bagrot	3250–3130	CB and PR
56	Ali <i>et al.</i> (2021)	Nalter	3096–3277	CB and CGR
<i>Pinus wallichiana</i>				
57	Ahmed and Sarangezai (1991)	Takht-e-suleiman, Ayubia, Khansupr and Murree.	2195–3048	CB and CGR
58	Ahmed <i>et al.</i> (2009b)	Sundhan Gali	1400–2700	GR and CGR
59	Ahmed <i>et al.</i> (2010b)	Astore	3450	CB and CGR
60	Ahmed <i>et al.</i> (2011)	Astore and Mushkin	2550–3450	CB and CGR
61	Bokhari <i>et al.</i> (2013)	Azad Kashmir	833–2900	CB and GR
62	Ali and Ali (2014)	Ganji (Skardu)	3310	CB and CGR
63	Asad <i>et al.</i> (2017b)	Bagrot	3550–3710	CB and TR
64	Asad <i>et al.</i> (2017a)	Shangla	1990–2810	GR and CGR
65	Asad and Zhu (2018)	Haramosh valley	3120–3450	CB and CGR
66	Asad <i>et al.</i> (2018)	Chiraah valley	3010–3350	CB and CGR
67	Khan <i>et al.</i> (2018a)	Main Murree	2291	CB and CGR
68	Iqbal <i>et al.</i> (2020)	Shangla	1990–2810	GR and CGR
69	Ali <i>et al.</i> (2021)	Phaphorash	3374–3504	CB and CGR
70	Luqman <i>et al.</i> (2021)	Chaprot and Haramosh	3020–3504	CB and CGR
71	Zhu <i>et al.</i> (2021)	Bagrot	3550–3710	CB, TR and earlywood cellulose $\delta^{18}\text{O}$
72	Huang <i>et al.</i> (2022)	Bagrot	3550–3710	latewood $\delta^{18}\text{O}$ chronology
<i>Pinus roxburghii</i>				
73	Ahmed and Sarangezai (1991)	Marghazar	1829	CB and CGR
74	Ahmed <i>et al.</i> (2009b)	Khatlan Bala, Lower Dir	1400–2700	GR and CGR
75	Bokhari <i>et al.</i> (2013)	Azad Kashmir	833–2900	CGR and DP
76	Khan <i>et al.</i> (2018a)	Ghora gali	2291	CB
77	Muhammad <i>et al.</i> (2021)	Kalam Forest Division	1900–4600	CB and CGR
<i>Taxus baccata</i>				
78	Muhammad <i>et al.</i> (2021)	Kalam	1900–4600	CB and CGR

The research field was standardized into nine domains: chronology building, climate-growth relationship, growth rate, climate reconstruction, temperature reconstruction, precipitation reconstruction, stable isotope analysis, dendroecological analysis and dendrohydrological analysis. Mid-elevation points were calculated for sites using $(\min + \max)/2$. We used SciPy, scikit-learn, statsmodels and pandas libraries in Python 3.11 for all analyses.

We have calculated the mean, median, standard deviation (SD), standard error of the mean (SEM), coefficient of variation (CV %), range and 95% confidence intervals (CIs) of the chronology-length mean, when $n \geq 2$ based on the t-distribution for each species. We reported the amount of research-effort as proportion with 95% CIs using the Wilson score, which is far superior to Wald-based CIs for small sample sizes and extreme proportions (Brown *et al.* 2001). The normality of chronology-length values was tested using the Shapiro–Wilk test. The test indicated non-normality ($W = 0.893$, $p = 0.022$) and so we used non-parametric tests to compare groups.

We used the Kruskal–Wallis H-test to examine variations in median chronology lengths across plants with $n \geq 2$ chronologies. This distributed-free alternative compared to one-way ANOVA is suitable due to the small and uneven sample sizes and the non-normal residual values of our data. We built an 11×9 contingency table (species $\times$ domain) and used the χ^2 test of independence to see if research domains are more likely to be used on certain species. We reported the χ^2 statistic, degrees of freedom, p-value and Cramér's V as an effect-size measure: $V = \sqrt{[\chi^2 / (N(k-1))]}$, where N is the total count and k is the smaller of rows or columns. The Shannon–Wiener index ($H' = -\sum p_i \ln p_i$), Simpson's diversity ($1-D = 1-\sum p_i^2$) and Pielou's evenness ($J' = H'/\ln S$) were used to measure how evenly research was done across species. Here, p_i is the fraction of studies for species i and S is species richness.

We looked at the link between the mean elevation of the research site and the maximum chronology length for each species using both Pearson product-moment (for linear relationship) and Spearman rank correlation (for linear association), which is strong against non-linearity and outliers. We employed ordinary the least-squares (OLS) regression along with residual analysis to get the slope, intercept, R^2 and 95% predicted bands.

We constructed a five-variable multivariate profile for each species, *i.e.*, number of research, mean altitude, elevation variance, mean time series length, number of study areas investigated and z-standardized all of the variables. We calculated principal component analysis (PCA) on the relationship matrix and reported the variance explained for each component. The same profile matrix was used for Ward's minimum-variance the hierarchical clustering method, *i.e.*, Euclidean distance based on standardized variables. The number of clusters was chosen by looking at the agglomeration schedule and then combining it with the PCA biplot matrix for cross-validation.

To find the elevational niche overlap between each pair of species, we used Pianka's index: $O = \sum (p_i q_i) /$

$\sqrt{[\sum p_i^2 \cdot \sum q_i^2]}$, in which p_i and q_i are the relative usage rates of corresponding species p and q in altitude bin i (500-m bins from 0 to 5000 m; ranges proportionately distributed). Values go from 0 (no overlap) to 1 (the same distribution). The Jaccard similarity index was used to measure how much research sites shared: $J(A,B) = |A \cap B| / |A \cup B|$, where both A and B are the sets of identified study areas for each species.

We showed the number of publications each year and the total number of publications each year. We then used OLS regression to find out how research output has grown over time. A species-accumulation curve was created by noting the year when each species first appeared in the literature. A two-tailed $\alpha = 0.05$ was used for all experiments. Statistical significance is shown by the following: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Results

Distribution of research efforts among species

Pinus wallichiana made up 20.5% of the 78 papers analyzed ($n = 16$, 95% Wilson CI 13.0–30.8%), subsequently followed by *Abies pindrow* (16.7%, 13 studies, 10.0–26.5%), *Picea smithiana* (15.4%, $n = 12$, 9.0–25.0%) and *Cedrus deodara* (14.1%, $n = 11$, 8.1–23.5%). These four species together account for 66.7% of all dendrochronological studies conducted in Pakistan (Fig. 2). The research effort for *Juniperus excelsa* and *Pinus gerardiana* was 7.7% ($n = 6$ each), whereas the research effort for *Pinus roxburghii* was 6.4% ($n = 5$). The other three *Juniperus* species made up 10.3% (8 studies), while *Taxus baccata* was the least investigated taxon (1.3%, one study).

Diversity of research efforts: Shannon, Simpson and Pielou

The research endeavor was quantitatively assessed using the Shannon–Wiener index, yielding $H' = 2.155$, which is close to the maximum attainable value ($H_{\max} = \ln 11 = 2.398$). Simpson's diversity ($1 - D$) = 0.867 and Pielou's evenness (J') = 0.899 show that research funding is spread out reasonably evenly across species, even though *P. wallichiana* seems to be the most common one. The findings suggest that dendrochronological research in Pakistan has been conducted on a diverse range of conifer species present in the study region. However, the sample sizes for *Juniperus* taxa and *Taxus baccata* are still not large enough for strong cross-species comparisons.

Length of chronology: descriptive statistics and the Kruskal–Wallis test

The 22 longest chronologies range from 51 to 1224 years, with an overall mean of 445 years (± 366 years), a median of 386 years and a CV of 82.2% (Fig. 3). The Shapiro–Wilk test rejected normality ($W = 0.893$, $p = 0.022$), which means that non-parametric methods were appropriate. The longest chronologies were observed for *Juniperus turkes-*

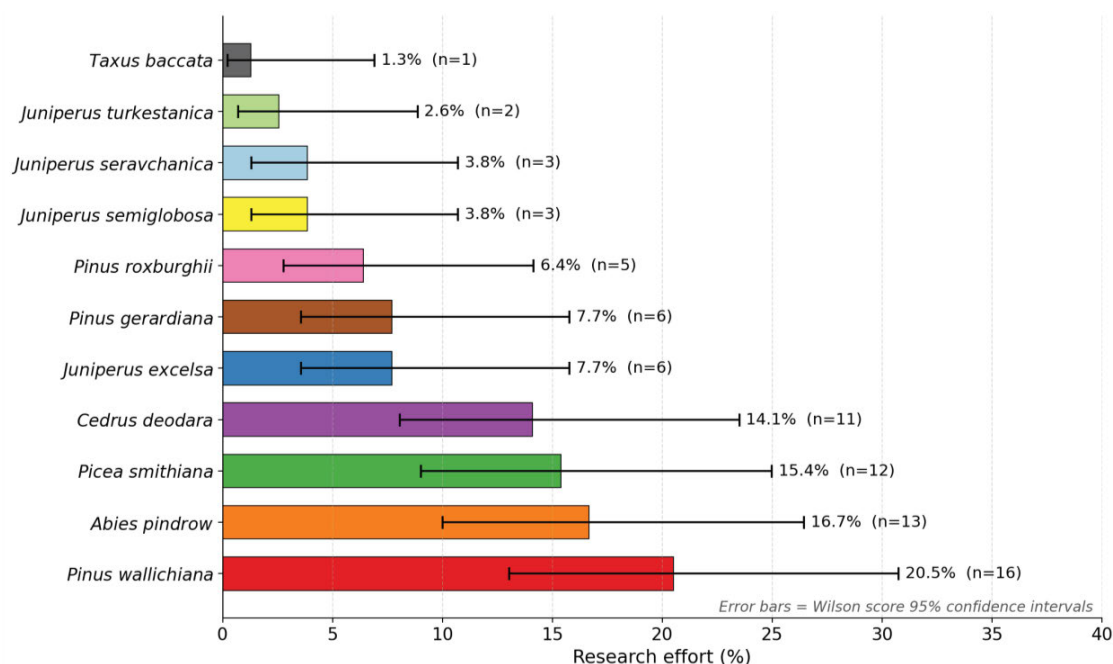


Fig. 2. Horizontal bar chart showing the eleven conifer species investigated in northern Pakistan ($n = 78$ studies, 1989–2022). The error bars reflect the 95% confidence intervals for the Wilson score. To the right of each bar, there are notes on the percentages and sample sizes. Four species, *Pinus wallichiana*, *Abies pindrow*, *Picea smithiana* and *Cedrus deodara* comprise two-thirds of all dendrochronological studies.

tanica and *Juniperus excelsa* (both 1224 yr, AD 950–1998), while the shortest were reported for *Cedrus deodara* (51 yr) and *Pinus roxburghii* (75 yr). The Kruskal–Wallis test for the five species with $n \geq 2$ chronologies produced $H = 7.30$, $df = 4$, $p = 0.121$, suggesting that although *Juniperus* species generally possess longer records, the available sample sizes are inadequate to establish statistical significance pairwise differences.

The rise of research output over time

Cumulative dendrochronological studies in Pakistan exhibited a robust and linear increase from 1989 to 2022, with OLS regression indicating a slope of 2.41 ± 0.17 studies/year, $R^2 = 0.860$ and $p < 0.001$ (Fig. 4A). The species-accumulation curve (Fig. 4B) shows that all eleven species were researched at least once by 2021. This means that the Pakistani dendrochronology

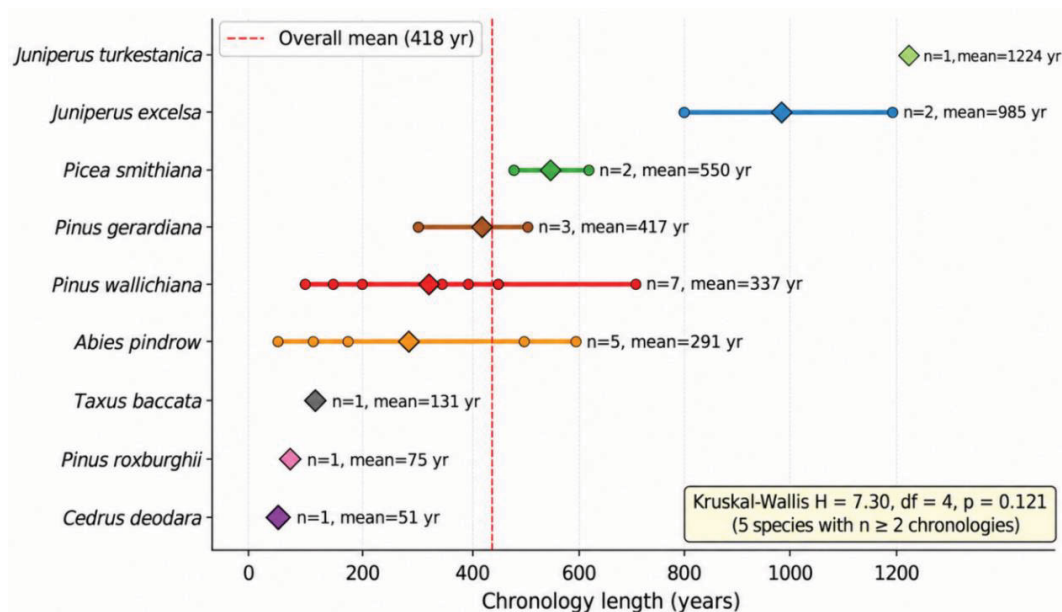


Fig. 3. A forest plot shows the ring-width chronologies length for each species. Colored bars show the measured range (or 95% CI for $n \geq 2$), whereas diamonds show species averages. Small dots show individual chronologies. The red dashed line shows the total means (445 years). The bottom right corner shows the result of the Kruskal–Wallis test ($H = 7.30$, $df = 4$, $p = 0.121$).

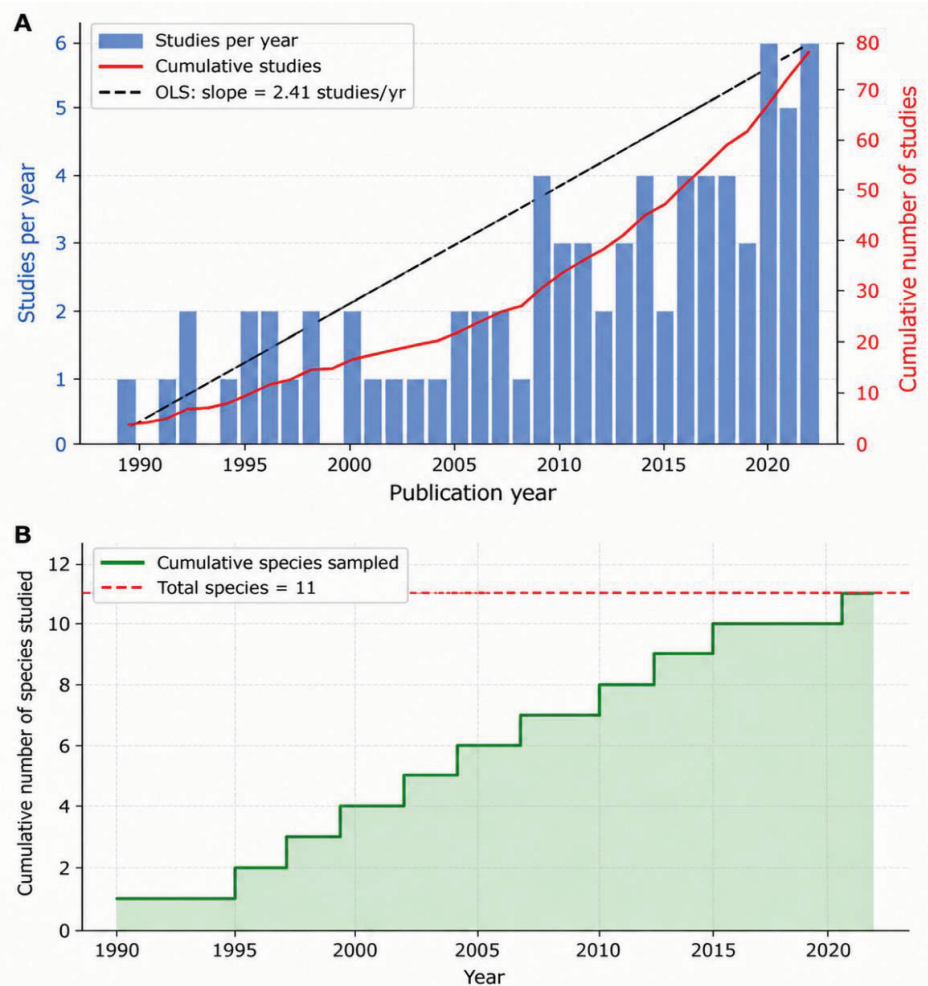


Fig. 4. The variation in time of dendrochronological studies conducted in Pakistan from 1989 to 2022. **(A)** The number of publications each year (blue bars on the left axis) and the number of cumulative studies (red line on the right axis) with an OLS trend line (dashed). The cumulative series is represented by the equation $y = 2.41 \text{ year} - 4786$, with $R^2 = 0.860$ and $p < 0.001$. **(B)** Curve of species accumulation. The green steps show the total number of different species that were sampled. By 2021, all eleven species have been discussed in the literature (red dashed line).

"species inventory" is almost complete. However, the quantity of sampling done on each species is still rather unequal.

The research locations' altitude distribution

The mid-point elevations of the study sites ranged from 274 to 4600 m a.s.l. The median elevations varied a lot between species (Fig. 5). *Pinus roxburghii* and *Taxus baccata* had the widest altitude ranges (833–4600 m), while the four *Juniperus* species were mostly found above 2700 m, which is what you would expect from their treeline ecology. *Cedrus deodara* and *Pinus gerardiana* had intermediate elevational distributions (1400–3450 m), indicating their wider ecological amplitude in the dry temperate forest region.

Relationship between elevation and length of chronology

A notable positive monotonic correlation was identified between the mean study-site elevation of species and the maximum chronology duration (Spearman $\rho = 0.703$,

$p = 0.035$; Pearson $r = 0.634$, $p = 0.067$). The OLS regression produced a slope of 0.665 yr m^{-1} , an intercept of -1221 and a R^2 value of 0.402 (Fig. 6). This trend shows that, on average, species collected at higher altitudes had the longest climatic histories. This is in accordance with the projected tree-longevity gradient currently the cold, stress-limited.

Coverage of research domains

Chronology Building (CB) is the most common research domain, with 57 occurrences across all studies. This is followed by Climate and Growth Association ($n = 47$), Growth Rate ($n = 14$), Climate Reconstruction ($n = 6$), Temperature Reconstruction ($n = 5$), Precipitations Reconstruction ($n = 4$) and lesser contributions from isotope analysis, dendroseismology analysis and dendrohydrology (Fig. 7). The chi-square statistic of independence ($\chi^2 = 82.90$, $df = 80$, $p = 0.390$; Cramér's $V = 0.272$) showed that research-domain choices are statistically independent of species identity, with an effect magnitude

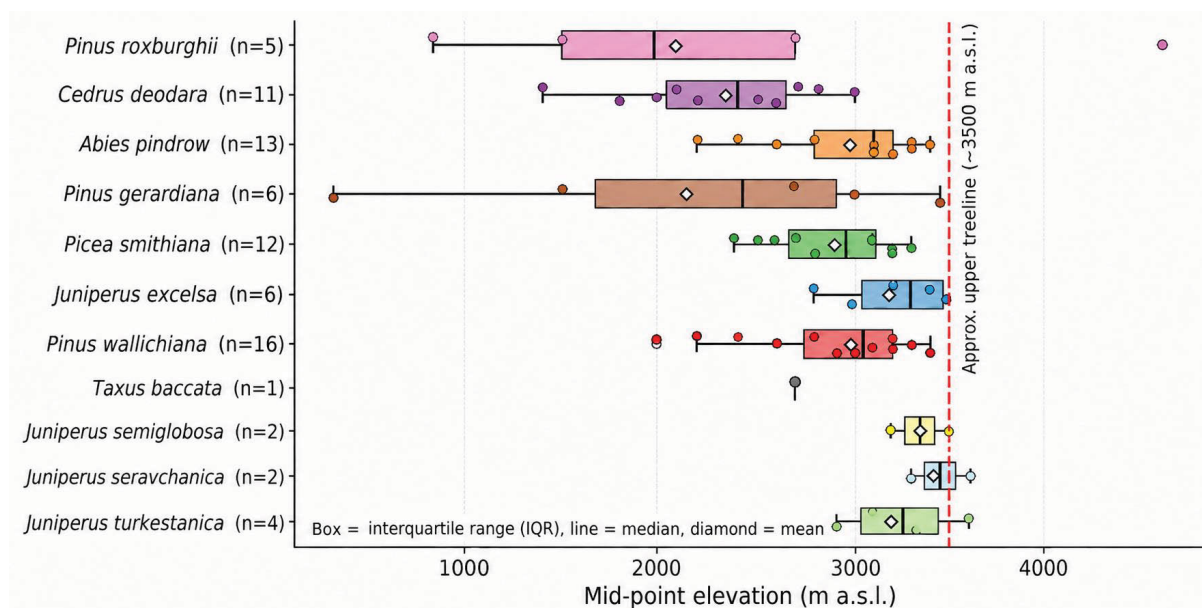


Fig. 5. The elevation the distribution of dendrochronological research sites per species. The boxes represent the median and interquartile range, the whiskers go up to 1.5 times the interquartile range (IQR) and the colored dots show the different research. The red dashed line shows the estimated top treeline of the Karakoram–Himalaya area, which is around 3600 m a.s.l. Above this boundary, the four species of *Juniperus* are quite close together.

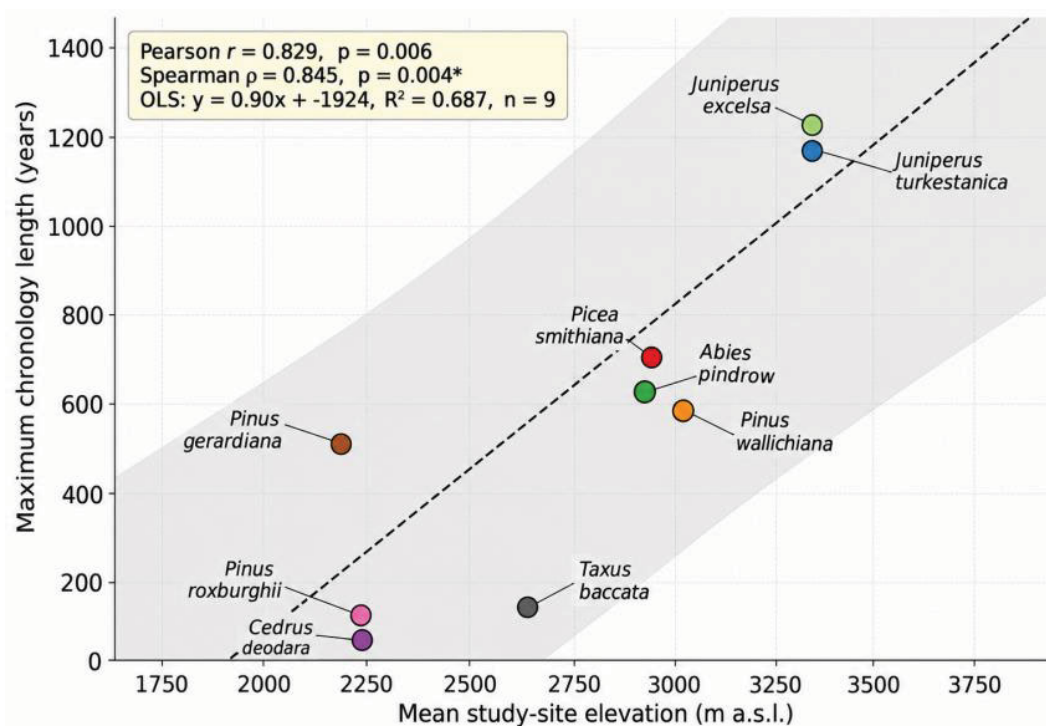


Fig. 6. A scatterplot showing the maximum duration of a chronology compared to the average elevation of a species' research location. The dashed line is the OLS regression with a 95% prediction band (grey). Each marker stands for one species (colored as in Fig. 2). Both of non-parametric (Spearman $\rho = 0.70$, $p = 0.035^*$) and a parametric (Pearson $r = 0.63$, $p = 0.067$) tests indicate a positive correlation.

that is relatively modest to moderate. This indicates that Pakistani dendrochronologists have extensively used the whole scientific toolset across all examined species, signifying a favorable indication of methodological advancement in the discipline.

Multivariate syntheses: principal component analysis and hierarchical clustering

Principal component analysis of the five-variable species profile (n studies, mean altitude, elevation range, mean chronology length, number of domains) accounted for

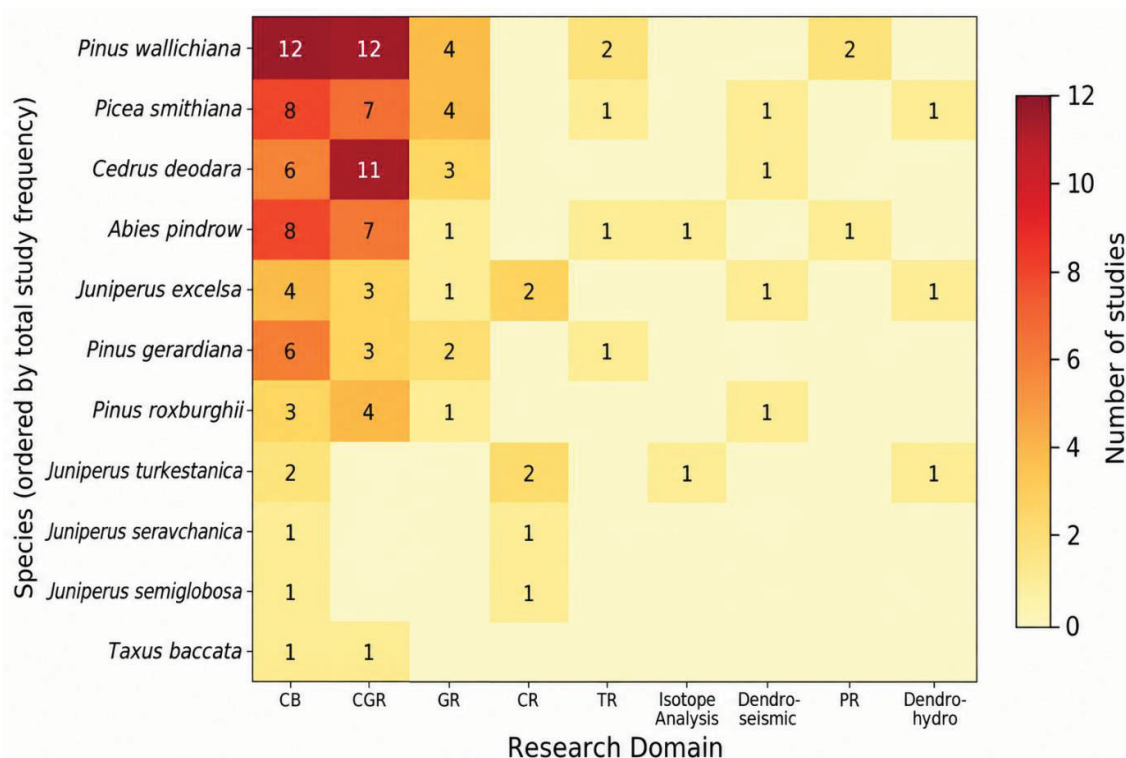


Fig. 7. Heatmap of species vs. research-domain frequency. Rows are sorted by total study frequency, from highest to lowest and columns are sorted by total occurrences, from highest to lowest. The numbers in the cells show the raw counts. The results show that there is no systematic specialization of study topics by species. The chi-square value is 82.9, the degrees of freedom are 80 and the p-value is 0.390. Cramér's V is 0.27, which means there is a weak to moderate connection. CGR stands for Climate-Growth Relationship, GR = Growth Rate, CR = Climate Reconstruction, TR = Temperature Reconstruction and PR = Precipitations Reconstruction.

87.5% of the total variation in the first two aspects (PC1 = 54.6%, PC2 = 32.9%; Fig. 8). Positive loadings of *n_studies*, *elev_range* and *n_domains* made up most of PC1. It also suggested a separation between extensively studied Pinaceae species (*A. pindrow*, *P. wallichiana*, *P. smithiana* and *C. deodara*) from species that were not investigated as much (*Taxus baccata*, *Juniperus semiglobosa* and *J. seravchanica*). Mean chronology length was the most important factor in PC2, which separated the long-chronology *Junipers*.

Three tentative groupings of species were distinguished by Ward's hierarchical clustering (Fig. 9): Cluster 1 (extensively studied Pinaceae with intermediate chronologies), Cluster 2 (rare or singularly studied species) and Cluster 3 (ancient *Junipers* with millennium-scale chronologies). The multivariate analyses, with relatively few species in each analysis, are presented for exploratory purposes only and do not constitute evidence of discrete groupings of species.

Overlap of elevational niches (Pianka's index)

The pairwise elevational niche-overlap values were between 0.24 and 1.00 (Fig. 10). The four *Juniperus* species showed nearly complete overlap ($O > 0.97$), confirming their tight ecological convergence at high-elevation tree-line habitats. *P. wallichiana* and *P. roxburghii* had a very wide range of elevations (833–4600 m) and it was quite

similar to most various species ($O = 0.70$ – 0.90). This shows that it is a generalist species. *Cedrus deodara* and *Pinus gerardiana* had the least overlap with the *Junipers* ($O < 0.50$), aligning with their lower-altitude, dry temperate habitat.

Sharing of study sites (Jaccard similarity) and violin-strip summary

Even though there was a lot of overlap in elevational niches, the Jaccard site-sharing index was consistently low across species pairings (max = 0.20). This means that species that live together are seldom sampled together in the same published research (Figs. 11 and 12). This pattern illustrates the conventional practice of single-species sample arrangements in Pakistani dendrochronology and underscores the potential for future multi-species sampling to provide direct cross-species response to climate change comparisons within a unified site framework.

Discussion

This review is the first to use a comprehensive set of descriptive in nature, inferential, multivariate analysis and ecological statistical approaches on the literature on dendrochronology in Pakistan. Compared to earlier qualitative summaries (Ahmed *et al.* 2011; Ali *et al.* 2021), our framework makes five new contributions: (i) quantitative uncer-

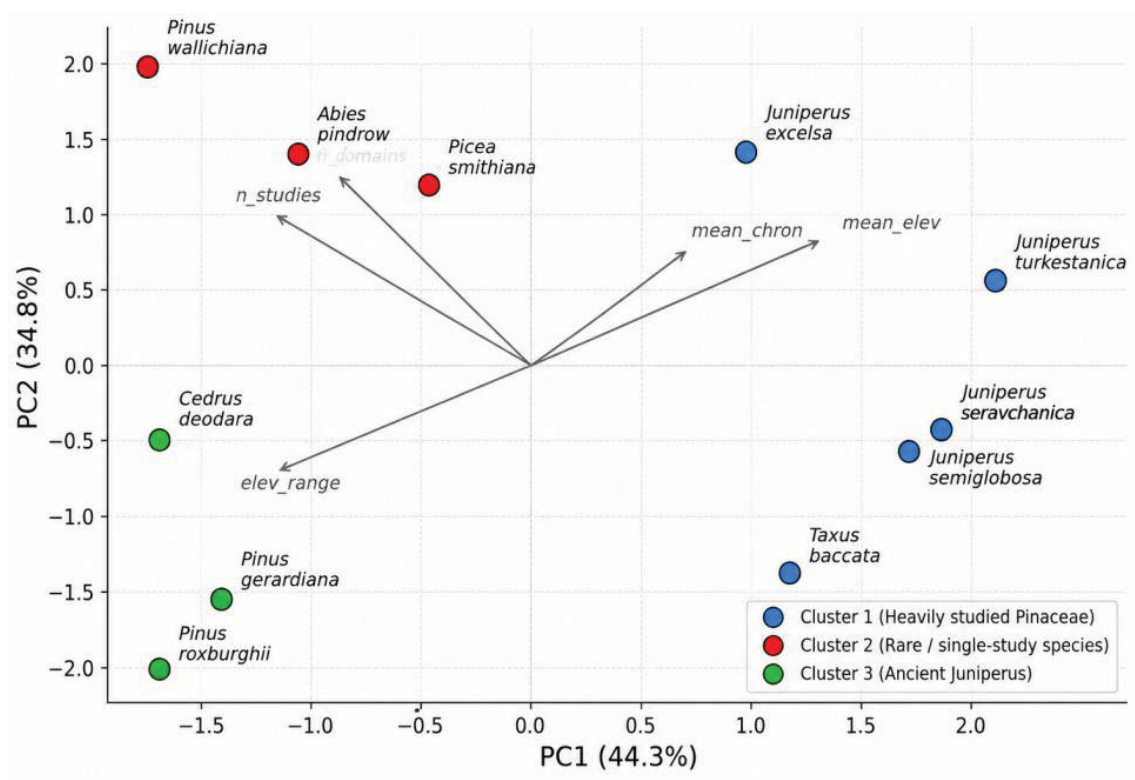


Fig. 8. Principal component analysis biplot shows the profile of species study. The points depict species that have been assigned to Ward clusters (blue = Cluster 1, red = Cluster 2, green = Cluster 3). The grey arrows show variable loadings, with the length of the arrow showing how much each variable contributes. PC1 (54.6%) shows how much research is done and how wide it is, while PC2 (32.9%) shows how deep it is over time. The total variation for PC1 and PC2 is 87.5%.

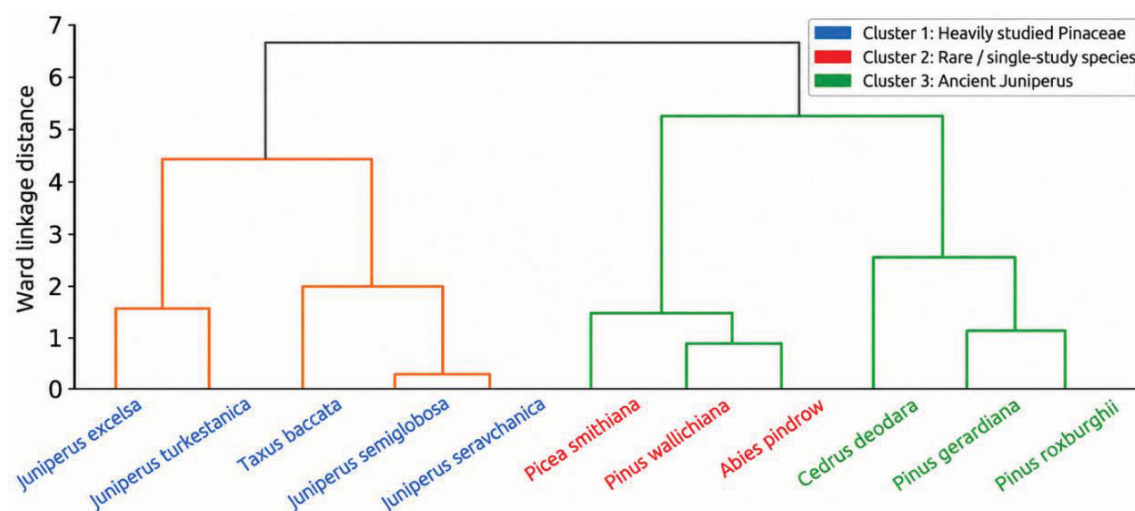


Fig. 9. Ward's technique and the Euclidean distance on the z-standardized profile variables were used to make a hierarchical clustering dendrogram. Three ecologically consistent groupings emerged (color-coded): Cluster 1 is made up of Pinaceae that have been examined a lot. Cluster 2 is made up of species that are uncommon or only investigated once, while Cluster 3 is made up of old *Junipers*. The names of the species are italicized and colored based on their cluster membership.

tainty (Wilson 95% CIs) for research-effort proportions, which allows for statistically sound comparisons; (ii) formal non-parametric testing of differences in chronology length (Kruskal–Wallis); (iii) information-theoretic diversity indices that measure research-effort evenness; (iv) multivariate ordination (PCA) and hierarchical clustering to group the species by their study profiles; and

(v) ecological niche-overlap (Pianka) and site-sharing (Jaccard) analyses to show the limits of sampling design. These methods turn a narrative examination into a data-driven synthesis that can be repeated and meets contemporary meta-analytic requirements.

The significant Spearman correlations ($\rho = 0.70$, $p = 0.035$) between the species' mean study-site altitude

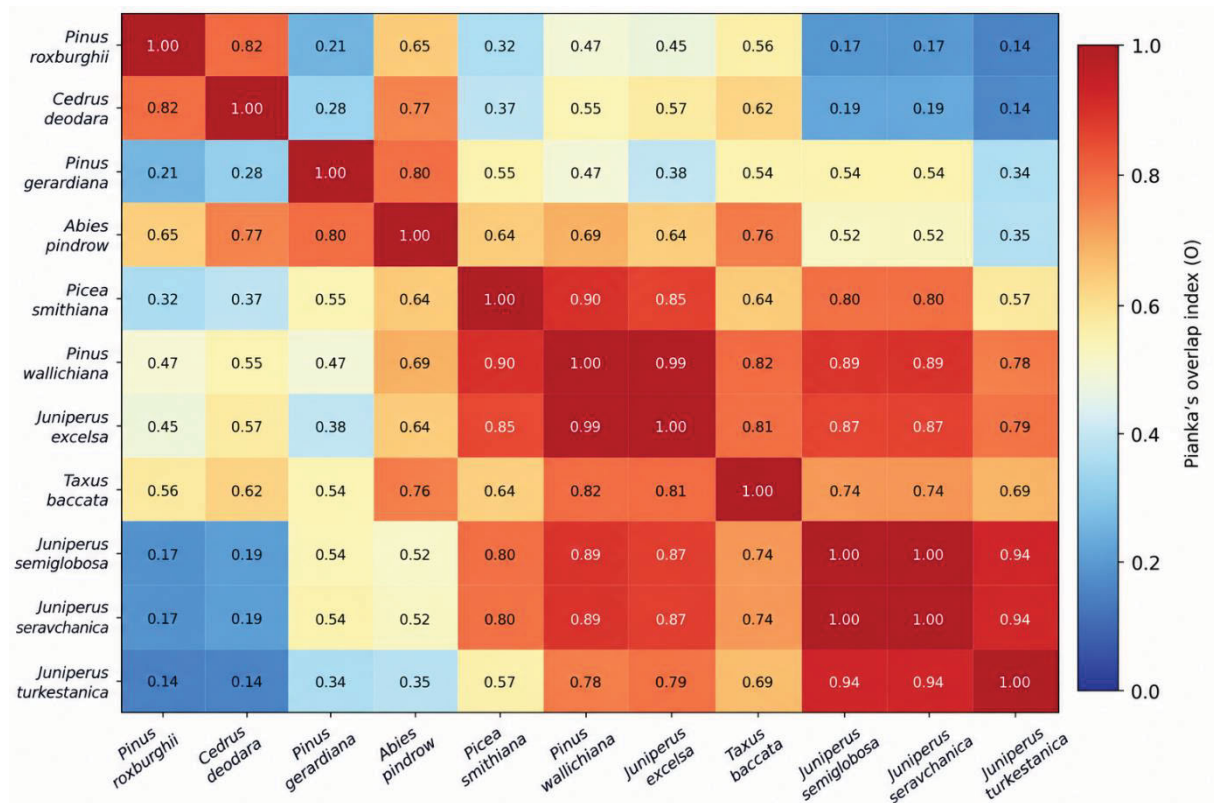


Fig. 10. A heatmap showing Pianka's elevation-based niche-overlap Pianka's index O across species, with 500-m bins. O may be anywhere from 0 (no overlap) to 1 (the same distribution). The mean elevation of each species is listed in order from lowest to highest. There is a lot of overlap across *Juniperus* species, which shows that they all have similar treeline ecology.

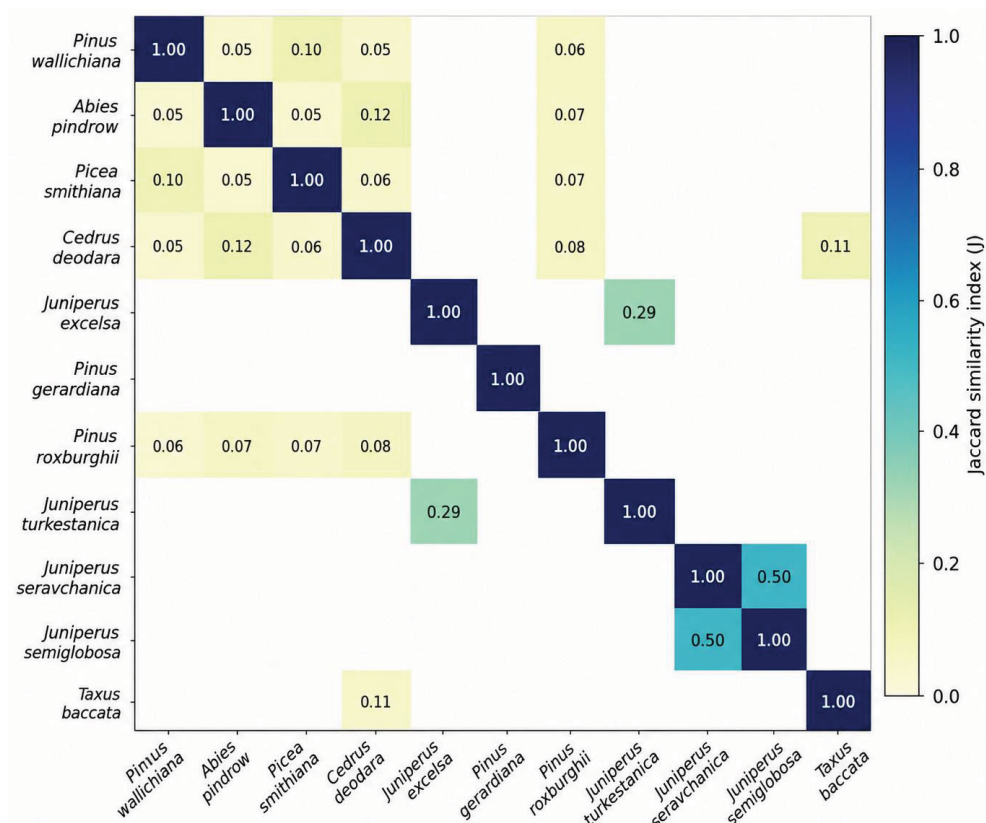


Fig. 11. A Jaccard similarity matrix for sharing research sites. $J = |A \cap B| / |A \cup B|$, where A and B are the groups of research areas for each species. Uniformly low results (max $J = 0.20$) show that most published studies only look at one species per site, which makes it hard to compare species directly within a site.

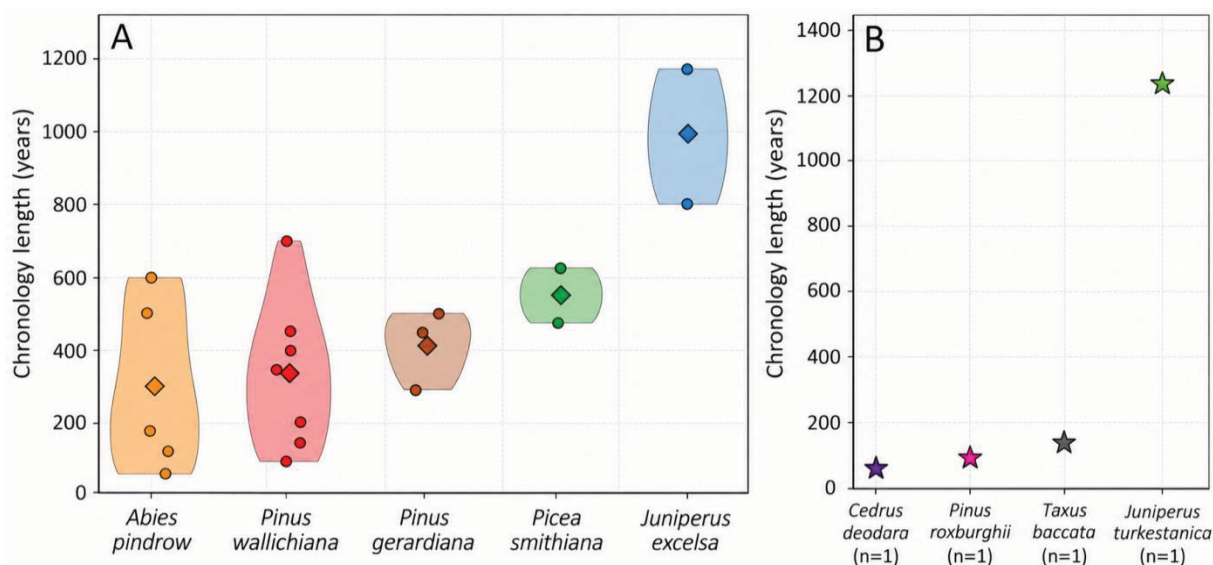


Fig. 12. Violin strip plot illustrating the lengths of chronologies for a species with $n \geq 2$ records (A) and a species with a single study (B). The violins show the kernel density estimation. The small circles show the unique chronologies, while the diamonds show the averages for each species. The fact that *Pinus wallichiana* may live for 106 to 700 years and *Abies pindrow* can live for 61 to 500 years indicates how varied the study sites were for these groupings.

and maximum chronology length corresponds with the recognized ecological principle that trees in cold, stress-limited treeline environments typically exhibit increased longevity and greater annual growth ring accumulation (Esper *et al.* 2002; Treydte *et al.* 2006; Asad *et al.* 2018). The four *Juniperus* species, which are only found above 2700 m and make up most of Pianka's niche-overlap cluster (Fig. 10), have the longest records in our dataset, lasting up to 1224 years. Their lengthy life spans and sensitivity to changes in precipitation at high heights (Esper *et al.* 2007; Iqbal *et al.* 2017) make them especially useful for putting together multi-millennial climatic histories in High Asia.

The same elevation-dependent relationships have been found in other high-altitude areas of High Asia. Tree growth and climatic sensitivity can significantly change along the elevation gradient in the studies from the Pamir-Alay and Tibetan Plateau which is related to different temperature, moisture availability and local site conditions (Qin *et al.* 2013; Opała-Owczarek *et al.* 2023). Similar growth and physiological responses to elevation have been observed in Himalayan fir, highlighting the general importance of elevation as a factor driving tree-ring variability in high mountain forests (Panthi *et al.* 2020; Khan *et al.* 2021).

The elevated Pielou's J' (0.90) and the insignificant species vs. domain interaction ($\chi^2 p = 0.39$, $V = 0.27$) signify that Pakistani dendrochronology has evolved into a methodologically advanced discipline, wherein the comprehensive array of dendrochronological techniques has been utilized across almost all species. This evenness, on the other hand, relates to the number of studies per species, not the total number of chronologies. Seven of the eleven species still have less than seven published chronological records apiece. This is a major problem that makes it hard to replicate results across sites, increases the density of

dendroclimatic networks and makes it harder to contribute to hemispheric temperature reconstruction (Zafar *et al.* 2016; Khan *et al.* 2018, 2020). Future study should focus on enhancing depth of replication for *Juniperus*, *Taxus baccata*, *Pinus gerardiana* and *Pinus roxburghii*.

A notable result was obtained by integrating Pianka's niche-overlap analysis (Fig. 10) with Jaccard site-sharing (Fig. 11). Even if a lot of species, notably the four *Juniperus* taxa, have almost the same elevational niches ($O > 0.97$), their Jaccard site overlap is always quite low ($J < 0.20$). This "niche-site sampling paradox" uncovers a significant methodological opportunity, *i.e.*, multi-species co-sampling designs that involve sampling multiple species within a single treeline site would facilitate direct comparative analyses of climate sensitivity, growth allocation and isotopic signatures, free from the confounding effects of between-site variation. Combining this design with contemporary stable-isotope ($\delta^{18}\text{O}$, $\delta^{13}\text{C}$) and blue-intensity techniques (Zhu *et al.* 2021; Huang *et al.* 2022) will significantly enhance the inferential capacity of the Pakistani tree-ring record.

Ward's hierarchical clustering (Fig. 9) and the PCA biplot (Fig. 8) showed broadly similar patterns, reflecting three exploratory species groupings that were based on the study intensity, elevational characteristics, chronology length and geographical or analytical coverage. Cluster 1 (*A. pindrow*, *C. deodara*, *P. smithiana*, *P. wallichiana*, *P. gerardiana* and *P. roxburghii*) had an intermediate number of chronology lengths, a wide elevational range and relatively high levels of research activity. This similarity indicates that these species are at present among the most rigorously studied species for dendrochronology in Pakistan. Cluster 2 (*J. semiglobosa*, *J. seravchanica* and *T. baccata*) includes species that are uncommon or only studied once and that do not span a wide range of time. This makes

them evident candidates for further sampling. Cluster 3 (*J. excelsa* and *J. turkestanica*) is the ancient juniper group with chronologies that go back thousands of years. These are already quite important for figuring out what the climate was like in Asia, but they would be much more useful if they were replicated more closely. However, note that these groupings are based on a relatively small number of species and are not definitive nor are they statistically proven. Rather, they offer an exploratory means of detecting species similarities and an aid to future sampling and dendrochronological studies. To test for the robustness and repeatability of these observed patterns, larger numbers of species, sites and chronologies must be studied.

The Third Pole perspective

The Pakistani Karakoram-Himalayas are a significant component of the larger Third Pole (High Mountain Asia; Fig. 1) region, with high reliefs, rugged topography and large glacier mass and high climatic variability. The region is under the control of the South Asian summer monsoon and mid-latitude westerly; hence the temperature and precipitation are highly variable in both space and time, whereas recent cooling boosts glacier resistance to global warming in the northern Karakoram (Liu *et al.* 2025). These aspects make Northern Pakistan especially important to explore environmental and climatic changes in high altitude ecosystems. The conifer species of Northern Pakistan, namely *Pinus wallichiana*, *Picea smithiana*, *Abies pindrow*, *Cedrus deodara* and *Juniperus* spp. have a high dendrochronological value. These species have been previously employed to reconstruct the temperature, precipitation, drought and other hydroclimatic changes spanning several centuries (Esper 2000; Ahmed *et al.* 2010a; Asad *et al.* 2023). Dendrochronological cover, however, is irregular and more studies are needed in other poorly documented species, elevations and mountain ranges.

Important goals and research problems

Several constraints must be acknowledged about the findings of this research. Initially, the assessment mostly relied on published research, therefore potentially failing to represent unpublished dissertations and gray literature. Secondly, the evaluations of chronology duration were based on the most extensive documented chronology for each species. This might exaggerate the historical extent of the species indicated by an exceptionally lengthy chronology. Third, the elevation data did not rely on the actual elevations of the sample sites, potentially impacting the clarity of species-specific elevational trends. Fourth, some analyzes, such the Kruskal-Wallis test and the elevation-chronology regression, exhibit less statistical power due to the limited sample size. The mathematical model suggested herein provides a consistent basis for forthcoming comprehensive meta-analyses.

Based on our study, we recommend the following directions for future dendroclimatological research in Paki-

stan. (1) The extension of the existing *Juniperus* chronology network, particularly the one established by Treydte *et al.* (2006), should focus on additional valleys, including Shimshal, Ghunsa, Yasin, and Ishkoman. Expanding geographic analysis would enhance spatial replication and allow for longer climatic reconstructions, extending beyond 1,000 years. (2) Further studies should aim to establish multi-species sample plots at treeline sites where two or more conifer species coexist in mixed forests. This approach would provide a comparable assessment of how different species respond to climate fluctuations under similar environmental conditions. Moreover, (3) greater emphasis needs to be placed on underrepresented taxa such as *Betula utilis*, *Abies spectabilis*, and *Rhododendron campanulatum*. Although these species have been extensively studied in India, Nepal, and China, they have been insufficiently included in dendrochronological research in Pakistan. (4) The use of stable oxygen-isotope ($\delta^{18}\text{O}$) analyses needs to be expanded to include additional species, such as *Juniperus* and *Cedrus*, and their application should continue as demonstrated by Zhu *et al.* (2021) and Huang *et al.* (2022). Additionally, measurements of blue intensity may be combined with ring-width data to offer a cost-effective method for enhancing climate reconstructions. Finally, (5) both existing and newly developed tree-ring chronologies from Pakistan should be uploaded to the International Tree-Ring Data Bank (ITRDB) along with the necessary information. Improved data accessibility will lead to enhanced repeatability, facilitate comparisons with other regions, and strengthen connections with the global dendrochronology network for Pakistan.

Conclusions

This systematic review has significantly enhanced the narrative of dendrochronology in Pakistan and has facilitated the development of a scientific, data-driven synthesis of the narrative. Out of the 78 studies and 22 longest chronologies examined, four Pinaceae species (*Pinus wallichiana*, *Abies pindrow*, *Picea smithiana* and *Cedrus deodara*) constituted the majority of study efforts (66.7%), but *Juniperus* species, although yielding the longest chronologies (up to 1224 years), were inadequately sampled. Important findings include: (i) a strong positive relationship between elevation and chronology length (Spearman $\rho = 0.70$, $p = 0.035$), (ii) a high level of evenness in research effort (Pielou $J' = 0.90$), (iii) the independence of research domains from species identity ($\chi^2 p = 0.39$) and (iv) three functionally coherent species clusters found by PCA (87.5% variance captured) and Ward clustering. These results create a quantitative plan for future dendrochronological research in the Karakoram-Himalaya area and set clear goals: more sampling of *Junipers*, using multi-species co-sampling designs, combining stable-isotope and blue-intensity methods and working with global tree-ring data infrastructure. We expect that this paradigm will lead to similar quantitative syntheses in other Asian dendrochronological areas and serve as a model for organizing

forest-climate research based on evidence. Future dendro-chronological research in Pakistan needs to be taken in the wider context of the Third Pole region, especially in the background of present-day climate change in high altitude regions. More tree ring data for more species, elevations and mountain ranges would enhance the understanding of climate and hydroclimatic variability in the past and bolster Pakistan role in regionally based climate reconstructions.

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